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# Forest residue maintenance increased the wood productivity of a *Eucalyptus* plantation over two short rotations

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ABSTRACT

Forest residue (i.e., litter layer, slash and bark), when used as biomass for energy production, represents an important strategy for use as a renewable energy source in many countries. However, these residues can also have importance as sources of nutrients for trees and soil conservation. The objectives of the present study were to assess the effects of forest residue management on soil, wood production and nutrient accumulation dynamics during two crop rotations in a *Eucalyptus grandis* plantation. Thus, we set up an experimental site with different intensities of removal, burning and incorporation of forest residues (first crop rotation of study – R1). The stands of all treatments were harvested after eight years, and the trial was re-established with all forest residues maintained on the soil across all treatments (second crop rotation of study – R2). R2 was conducted for eight more years. The growth and nutritional status, biomass and nutrient accumulation of the trees were assessed. The forest residue burn increased the initial nutrient availability in the soil; however, this availability returned to initial levels in a short period of time. Wood productivity decreased by approximately 40% with the removal of all forest residues in R1. In R2, wood productivity after the removal or burning of forest residues was 6% lower than when all forest residues were maintained on the soil.

## 1. Introduction

In Brazil, *Eucalyptus* plantations are often established in areas that have low agricultural potential, as characterized by low soil fertility and low mineral reserves (e.g., Oxisols and Entisols Psamments) (Gonçalves et al., 2013). High productivity levels (39 $m^3$ $ha^{-1}$ $year^{-1}$ of wood) were achieved under these conditions (IBÁ, 2015), reflecting favourable climatic conditions, genetic adaptation, appropriate management and fertilizer application as well as a high nutrient uptake capacity and usage (Barros et al., 2000; Laclau et al., 2010b, 2013).

Despite high *Eucalyptus* productivity, sustainability has become an increasingly important issue for planted forests in the medium and long-term, reflecting the low fertility of soil used for forest plantations. Organic matter largely influences the dynamics of the nutrients in these soils (Tiessen et al., 1994) and might reflect significant changes in the stock of soil nutrients for trees (Kumar and Goh, 2000). Thus, the maintenance of forest residues (i.e., litter layer, slash and bark) between rotations is essential to maintain or improve soil fertility and forest production sustainability (Huang et al., 2013; Kumaraswamy et al., 2014; Mendham et al., 2002; Tiessen et al., 1994; Achat et al., 2015). The effects of forest residue removal on wood productivity and soil fertility have been extensively studied (e.g., Huang et al., 2013; Kumaraswamy et al., 2014; Mendham et al., 2002, 2014); however, the potential site recovery after a previous rotation with residue removal is not known.

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Until the 1980s, in Brazil, forest residues were considered to be obstacles for the re-establishment of *Eucalyptus* plantations, motivating burn, removal or incorporation into soil. The concept that *Eucalyptus* plantations demand intensive soil preparation to achieve good yields was also considered to be a suitable management practice. Currently, most forestlands are established under a minimum or no tillage system (Gonçalves et al., 2013). However, with the restrictions on land use and elevation of fossil fuel prices, these residues were considered to be potential alternative power sources for the industrial sector. The benefits of residue maintenance on soil cannot to be neglected, despite their potential use as a renewable energy source (Achat et al., 2015). Thus, the sustainability of forest productivity will be ensured for future rotations.

The objectives of the present study were to: (i) assess the impact of contrasting inter-rotation management on stand productivity in low-fertility soil; (ii) explore the nature and extension of the maintenance or recovery of productivity from adverse impacts in response to conservative management during the second rotation; and (iii) discuss results with respect to biomass harvest for bioenergy and changes in soil properties.

## 2. Material and methods

### 2.1. Site description and treatments

This study was conducted in a commercial plantation at the municipality of Itatinga, São Paulo state (23°17′S and 48°28′O and 649 m above sea level). This region has a humid subtropical climate (Köppen climate classification Cfa) characterized by hot and humid summers with a mean annual temperature of 19.4 °C; 15.6 °C is the mean temperature in the coldest month (July) and 22.3 °C is the mean temperature in the hottest month (January). The historical mean (last 30 years) annual rainfall is 1300 mm, with 75% concentrated between October and March (Alvares et al., 2013). In the first crop rotation of the study (R1), between 1995 and 2003, the mean annual rainfall was 1600 mm and the mean annual temperature was 22.5 °C. In the second crop rotation of the study (R2), between 2004 and 2012, the mean annual rainfall was 1400 mm and the mean annual temperature was 22.0 °C.

The native vegetation of the site was the Cerrado *stricto sensu* (Brazilian savanna). This site has been planted with *Eucalyptus* species since 1974. The site was cropped with *Eucalyptus saligna* from 1974 to 1988 and with *Eucalyptus grandis* from 1988 to 1995. The local topography is flat, with deep Haplic Ferralsol, loamy, dystrophic (red-yellow Latosol) soil developed on cretaceous sandstone (Table 1). The mineralogy is dominated with quartz, kaolinite and oxyhydroxides.

The trial was a randomized complete block design with four replications. The measured plot comprised 49 plants distributed in 7 rows of 7 plants, with a double row buffer. Five treatments were assessed: (i) FRM - All forest residues were maintained on the soil, but only stemwood was harvested; (ii) LiM - only litter was maintained on the soil (all slash, stemwood and bark were removed); (iii) FRR - all forest residues (litter layer, slash and bark) were removed; (iv) FRI - all forest residues were incorporated into the soil at a depth of 0.2 m, with heavy harrow; and (v) FRB – all forest residues were burnt on the soil. The stands of all treatments were harvested after eight years, and the trial was re-established with all forest residues maintained across all treatments when the second rotation was planted.

### 2.2. Site management

In September of 1995, after the clear cutting of the previous *Eucalyptus grandis* plantation, the treatments were applied and the planting line was subsoiled at a depth of 0.4 m. The base fertilizer (15 kg ha$^{-1}$ of N, 13 kg ha$^{-1}$ of P and 12 kg ha$^{-1}$ of K) was applied to all treatments. The seedlings of a monoprogeny (full-sib) of *Eucalyptus grandis* Hill Ex Maiden were planted, with a 3 m × 2 m spacing. Eight months after planting, topdressing fertilization (124 kg ha$^{-1}$ of K) was applied in every treatment.

The experimental site was harvested in September of 2004, and all forest residues were maintained on the soil in all treatments. Two months after harvest, the same genetic material was planted in pits generated between the stumps at the same spacing as used in R1. Thus, it was possible to assess the residual effect of treatments applied in R1. The same fertilizer application as applied in R1 was used. The experimental site was maintained free of weeds through both crop rotations. Additional details about the set up and management of the trial are provided in Gonçalves et al. (2007, 2008).

### 2.3. Soil sampling and analysis

Soil samples were collected from 0 to 5, 5 to 10 and 10 to 20 cm layers. In R1, soil samples were collected at 1, 6 and 10 months and 2 and 6 years after treatment application, and in R2, soil samples were collected at 2, 4 and 7 years after planting (11, 13 and 16 years after treatment application in R1). Ten single samples were withdrawn to form a composite sample per plot, followed by sieving at 2 mm. The available P and exchangeable Ca, Mg and K were displaced using ion-exchange resins, and the pH was measured in a 0.01 mol L$^{-1}$ $CaCl_2$ solution (van Raij et al., 2001). The soil organic carbon (SOC) was determined through wet oxidation (Walkley and Black, 1934), and the soil total N was determined using the micro-Kjeldahl method (Bremner, 1965).

**Table 1**
Soil physical and chemical attributes of the study site.

| Depth (cm) | Sand (g kg$^{-1}$) | Silt (g kg$^{-1}$) | Clay[a] (g kg$^{-1}$) | Bulk density (g cm$^{-3}$) | pH[b] | C[c] (g kg$^{-1}$) | N[d] (g kg$^{-1}$) | P[e] (mg kg$^{-1}$) | Cation exchange[e] (mmol$_c$ kg$^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | K | Ca | Mg | Al |
| 0–10 | 770 | 30 | 200 | 1.25 | 3.5 | 15.2 | 1.8 | 6.0 | 0.4 | 1.7 | 1.5 | 14.5 |
| 10–20 | 770 | 30 | 200 | 1.25 | 3.6 | 10.5 | 1.0 | 4.5 | 0.3 | 1.4 | 1.2 | 11.5 |
| 20–30 | 760 | 20 | 220 | 1.30 | 3.7 | 9.3 | 0.9 | 3.0 | 0.3 | 0.9 | 0.6 | 12.0 |
| 30–50 | 760 | 20 | 220 | 1.30 | 3.8 | 4.6 | 0.5 | 3.0 | 0.2 | 0.5 | 0.3 | 11.0 |
| 50–100 | 740 | 20 | 240 | 1.31 | 3.8 | 1.5 | 0.2 | 2.0 | 0.2 | 0.5 | 0.3 | 11.2 |

[a] Pipette method (EMBRAPA, 2013).
[b] $CaCl_2$ 0.01 mol L$^{-1}$, soil to solution ratio 1:2.5.
[c] Wet oxidation.
[d] Sulfuric acid extraction.
[e] Ion exchange resin (van Raij et al., 2001).

### 2.4. Tree growth

In both rotations, the diameters at breast height (DBH) and total tree height (H) were measured annually. Two average trees were harvested annually to assess the aboveground biomass. From the second to the eighth year, in both rotations, the production of leaves, branches, bark and wood was quantified. The solid volume was calculated using Smalian's equation (Scolforo and Thiersch, 2004), with diameters measured every meter until reaching a minimum diameter of 3 cm.

Trees were separated into the following compartments: leaves, branches, stemwood (diameter > 3 cm at the thinner end) and stem bark. Sub-samples were collected from all of the compartments and dried (65 °C) until reaching a constant weight, and then, the dry biomass of the compartments in each tree was proportionally calculated. To estimate the wood, bark biomass and stem volume of the plantation from the sampled trees, DBH and H were used as independent variables for the model adjustment according to Schumacher and Hall (1933). To estimate the parameters of the equations, the data from all felled trees, regardless of age and treatment, totalling 72 trees in R1 and 60 trees in R2, were used. To estimate the biomass of the leaves and branches, linear and quadratic models were adjusted. The data from the felled trees were grouped annually. The grouping was based on a covariance analysis. The product of DBH squared with H was used as an independent variable. The parameters were estimated using SAS PROC REG 9.1 for Windows, and the model (Schumacher and Hall, 1933) was linearized.

### 2.5. Nutrients concentration

In both rotations, the nutrient concentration (N, P, K, Ca, Mg and S) in the aboveground components (leaf, branch, bark and wood) was determined in the second, fourth and eighth year, following establishment. After sulphuric digestion, total N was determined using the micro Kjeldahl method. After nitric perchloric digestion, P was determined through colourimetry, S was determined through turbidimetry, K was determined through flame photometry and Ca and Mg were determined through atomic absorption (Malavolta et al., 1989).

### 2.6. Nutrient balance

Biomass and nutrient stocks of previous rotations were assessed prior to harvest. Nutrient stocks in the tree components (leaves, branches, litter and bark) were used as the basis to predict the forest residue nutrient contents in response to each treatment. The nutritional balance was estimated for the FRM, LiM and FRR treatments. For the nutritional balance, the inputs considered the local atmospheric deposition (Laclau et al., 2010b) and the fertilizer application. N inputs through biological fixation were not considered, reflecting the low biological fixation of N by organisms (Fisher and Binkley, 2000) and absence of weeds. In addition, the input of rock weathering was also not considered, as the soil was highly weathered (Ferralsol). Harvesting was considered as an output. The root biomass was estimated using the allometric equations of Mello and Goncalves (2008), deduced at a site near the study environment with the same genetic material.

### 2.7. Data analysis

All data were normalized (Shapiro-Wilk), and the homoscedasticity was tested (Box-Cox). The F test was applied to assess differences between treatments. Principal Components Analysis was used to assess the soil nutrient contrast, and the data were separated according to soil layer (0–5 and 0–20 cm). Tree growth was analysed using a variety of sources: treatment, age, age × treatment interaction and block. These data were subjected to the LSD test at 5% significance for average comparison when the F test was significant ($p < 0.05$). The statistical software SAS 9.1 for Windows was used for data analysis.

## 3. Results

### 3.1. Soil fertility

The soil pH of the 0–20 cm layer was approximately 3.9 ± 0.1 and showed no change over the two rotations. There was no significant effect of site management on the soil pH in this layer (data not shown). When the 0–5 cm soil layer was considered, a significant, but temporary, increase in pH was observed with forest residue burn. Soil organic carbon (SOC) ranged from 6 to 13 g $kg^{-1}$, and the N ranged from 0.5 to 0.9 g $kg^{-1}$ in the 0–20 cm soil layer (Fig. 1). SOC and N were reduced until 6 years after treatment application, increasing for 11 years thereafter and maintaining levels of approximately 10 g $kg^{-1}$ of SOC and 0.8 g $kg^{-1}$ of N until 16 years after treatment application. The FRR showed the lowest amount of SOC and N until 11 years after treatment application. After this age, there was no significant effect of the treatments in SOC and N. There was no difference in SOC over two rotations

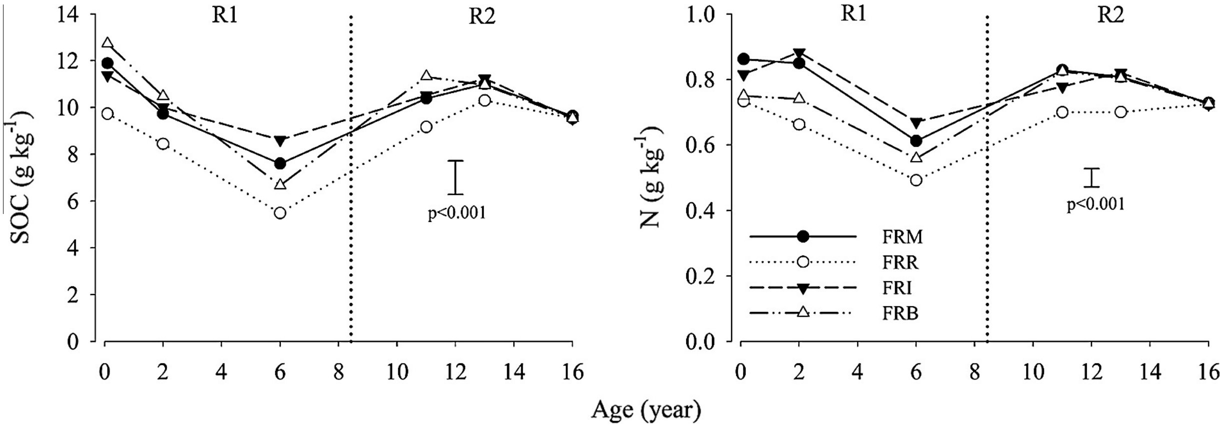

**Fig. 1.** Soil organic carbon (SOC) and soil N from 1 month to 16 years (two rotations) in the 0–20 cm layer after different forest residue management strategies. Treatments: FRM - All forest residues were maintained on the soil, only stem wood harvest, FRR - All forest residues removal, FRI - All forest residues were incorporated in the soil at 0.2 m deep with heavy harrow and FRB – All forest residues on the soil were burn. The bars indicate the least significant difference based on the LSD test at 5% probability, and the values under the bars show the significance of the F test.

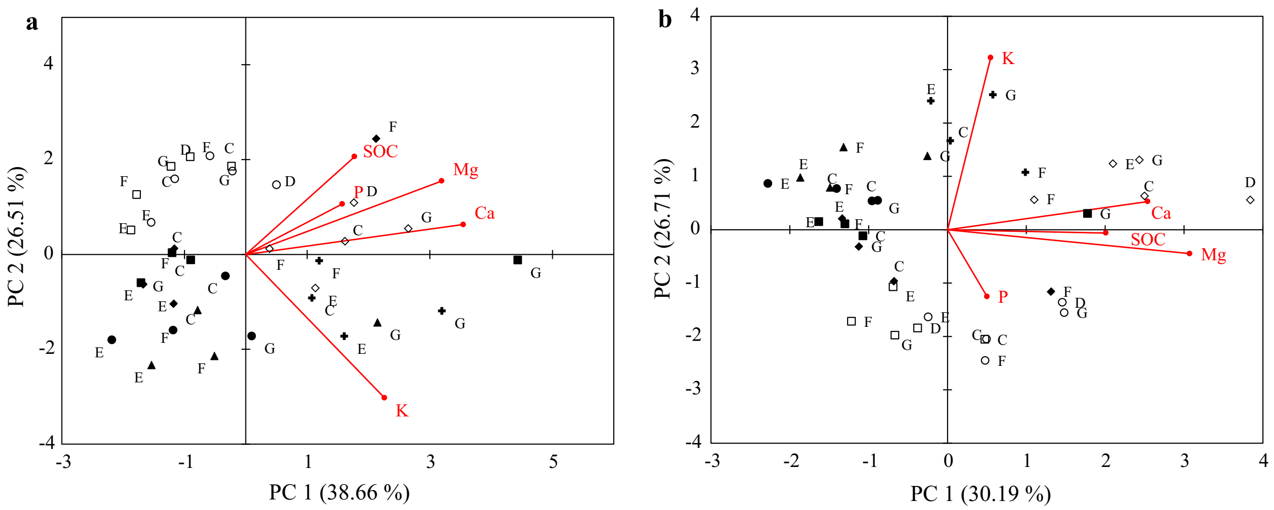

Fig. 2. Principal Component Analysis with the amount of exchangeable Ca, Mg and K available P and soil organic carbon (SOC) at the 0–5 cm (a) and 0–20 cm (b) soil layers with FRM (C), LiM (D), FRR (E), FRI (F) and FRB (G) treatments at 0, 1 (■), 0.5 (●), 0.8 (▲), 2 (+), 6 (◆), 11 (◇), 13 (○) and 16 (□) years after treatment application. The black filled symbols represent the first crop rotation, and the unfilled symbols represent the second crop rotation.

**Table 2**
Average (n = 4) of P, exchangeable Ca, Mg and K at the 0–20 cm layer in two crop rotations under different forest residue management strategies.

| Age[a] | Treatments[b] | | | | | | | | Treatments | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | FRM | | FRR | | FRI | | FRB | | FRM | | FRR | | FRI | | FRB | |
| | P (mg kg$^{-1}$) | | | | | | | | K (mmol$_c$ kg$^{-1}$) | | | | | | | |
| 0.1 | 4.0 | (2.1)[c] | 3.3 | (1.4) | 2.7 | (1.2) | 5.8 | (2.0) | 0.3 | (0.1) | 0.3 | (0.1) | 0.4 | (0.1) | 0.4 | (0.1) |
| 2.0 | 3.1 | (0.2) | 2.7 | (0.7) | 3.2 | (0.6) | 4.3 | (1.7) | 0.8 | (0.1) | 1.1 | (0.3) | 0.8 | (0.1) | 1.5 | (0.1) |
| 6.0 | 6.2 | (0.0) | 4.1 | (0.5) | 6.0 | (1.5) | 4.6 | (0.8) | 0.4 | (0.1) | 0.3 | (0.1) | 0.3 | (0.0) | 0.2 | (0.0) |
| 11.0[d] | 5.1 | (0.6) | 4.2 | (1.7) | 3.8 | (0.1) | 3.7 | (0.7) | 0.9 | (0.3) | 0.7 | (0.2) | 0.9 | (0.2) | 0.8 | (0.4) |
| 13.0 | 4.9 | (0.3) | 4.9 | (0.1) | 5.7 | (1.5) | 4.5 | (0.2) | 0.2 | (0.1) | 0.2 | (0.1) | 0.2 | (0.1) | 0.3 | (0.1) |
| 16.0 | 6.1 | (1.1) | 3.9 | (0.4) | 4.1 | (0.7) | 4.1 | (0.6) | 0.3 | (0.0) | 0.4 | (0.1) | 0.4 | (0.1) | 0.3 | (0.1) |
| | Ca (mmol$_c$ kg$^{-1}$) | | | | | | | | Mg (mmol$_c$ kg$^{-1}$) | | | | | | | |
| 0.1 | 2.6 | (0.4) | 2.4 | (0.6) | 2.7 | (0.3) | 4.6 | (0.9) | 0.4 | (0.2) | 0.3 | (0.2) | 0.4 | (0.2) | 1.4 | (0.6) |
| 2.0 | 1.8 | (0.6) | 2.0 | (0.3) | 1.7 | (0.6) | 2.2 | (0.7) | 1.8 | (0.7) | 1.8 | (0.4) | 2.0 | (0.5) | 1.8 | (0.2) |
| 6.0 | 1.5 | (0.2) | 1.5 | (0.1) | 2.7 | (0.7) | 1.4 | (0.7) | 1.3 | (0.0) | 1.1 | (0.1) | 2.7 | (0.5) | 1.2 | (0.5) |
| 11.0 | 3.0 | (0.8) | 3.5 | (1.0) | 2.5 | (0.6) | 2.8 | (0.6) | 2.4 | (0.4) | 2.1 | (0.4) | 1.8 | (0.2) | 2.6 | (0.2) |
| 13.0 | 2.0 | (0.3) | 1.5 | (0.2) | 2.0 | (0.3) | 2.8 | (0.5) | 2.3 | (0.2) | 2.1 | (0.4) | 1.8 | (0.2) | 2.5 | (0.8) |
| 16.0 | 2.3 | (0.2) | 1.4 | (0.5) | 1.3 | (0.3) | 1.4 | (0.1) | 1.8 | (0.4) | 1.6 | (0.7) | 1.1 | (0.4) | 1.2 | (0.2) |

[a] Years after treatment application.
[b] FRM - All forest residues were maintained on the soil, only stem wood harvest, FRR - All forest residues removal, FRI - All forest residues were incorporated in the soil at 0.2 m deep with heavy harrow and FRB – All forest residues on the soil were burned.
[c] Standard deviations.
[d] Second year of second study rotation.

between FRM, FRI and FRB. FRB reduced the N until 2 years after treatment application.

Principal components analysis was used to determine of the effects of forest residue management and age on some of the chemical soil properties. According to the Kaiser (1958) parameters, variance of the data set (P, K, Ca and Mg available, pH and OM) could be represented using two Principal Components (PC). The first two PC explain 65% of the variance of the dataset in the 0–5 cm soil layer and 60% of the variance in the 0–20 cm soil layer (Fig. 2a and b).

A large difference between treatments was observed at one month after treatment application. The highest amount of exchangeable bases and available P were observed after FRB treatment, and the lowest amount of exchangeable bases and available P, at the same age, were observed after FRR (Fig. 2 and Table 2). The difference in the nutrient availability was larger in the 0–5 cm layer (Fig. 2). The difference between FRB, FRM and FRI decreased with increasing age, but the FRR maintained the smaller amounts of exchangeable bases and SOC for 11 years after treatment application. The smallest amounts of P, Ca and Mg available at 6 years after treatment application (R1) were observed after FRR and FRB. An increase of exchangeable bases and SOC at 10 and 26 months after treatment application was observed in all treatments (Fig. 2a). At 11 years after treatment application and two years after R2, an increase in the amount of exchangeable bases and SOC was observed, primarily in the 0–5 cm soil layer.

### 3.2. Tree growth

Tree survival was higher than 95% in all plots. Forest residue management influenced ($p < 0.01$) tree growth until the end of R2. The FRB and FRI treatments in R1 exhibited the largest growth during the initial stages. The stem volume with bark at 2.5 years under these treatments was 30% higher than in FRM. At the same age, a 60% smaller standing volume was observed in FRR compared with FRM. From 5.5 years, there were no differences between FRM,

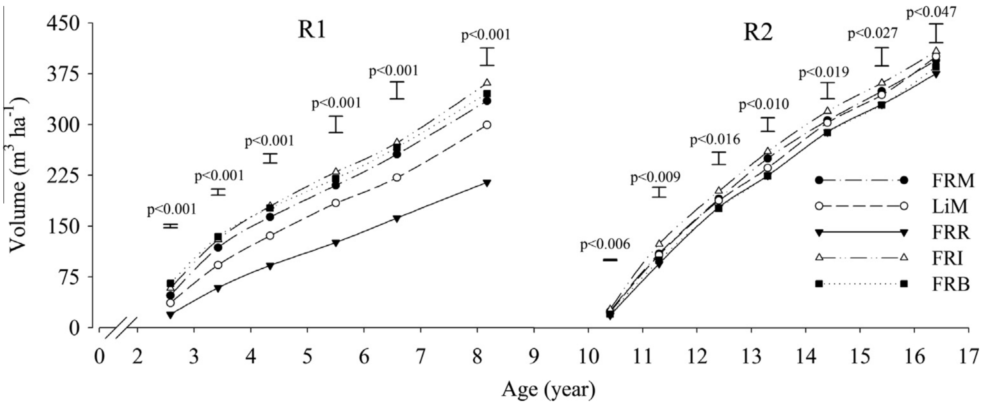

**Fig. 3.** Solid wood volume with increasing age in two crop rotations under different forest residue management strategies. a – first crop rotation (R1) and b – second crop rotation (R2). Treatments: FRM - All forest residues were maintained on the soil, only stem wood harvest, FRR - All forest residues removal, FRI - All forest residues were incorporated in the soil at 0.2 m deep with heavy harrow and FRB – All forest residues on the soil were burned. The bars indicate the least significant difference using the LSD test at 5% probability, and the values on the bars show the significance of the F test.

FRB and FRI. These treatments had the same stem volume (350 $m^3$ $ha^{-1}$) at the end of R1 (eight years). At eight years, forest residue removal (FRR) reduced approximately 40% of the stem volume and 15% of the bark and slash removal (LiM) (Fig. 3).

There was a residual effect of forest residue in R2 (Fig. 3). In the FRR and FRB treatments, at 2.2 years, a 28% reduction in the stem volume was observed compared with FRM and FRI treatments. The standing volume at the end of R2 was 400 $m^3$ $ha^{-1}$ in the FRM and FRI treatments and 375 $m^3$ $ha^{-1}$ in the FRR and FRB treatments (6% reduction).

### 3.3. Biomass and nutrient accumulation

Biomass accumulation was higher in FRB, FRI and FRM (175 Mg $ha^{-1}$) than FRR (100 Mg $ha^{-1}$) in R1 (data not shown). In all treatments, the same proportion of leaves, branches, bark and wood in the total biomass was observed, with larger differences observed with stand age. After 2 years, the aboveground biomass comprised 60% wood, 9% bark, 10% branch, and 21% leaf. Wood contribution increased until four years after planting, followed by decreased leaf and branch contribution and stabilization after this age. At the end of the rotation, wood represented 90%, bark represented 6%, branch represented 2% and the leaf contribution represented 2% of the aboveground biomass.

FRI and FRB showed higher nutrient accumulation in the aboveground compartments after 2 years during R1 (Fig. 4). Nutrient accumulation was the same for FRM, FRI and FRB at four years after planting. At 8 years, the aboveground compartments in FRM, FRI and FRB accumulated approximately 350, 50, 200, 60 and 55 kg $ha^{-1}$ of N, P, Ca, Mg and S, respectively. Potassium uptake differed among the fastest growing treatments: in FRM and FRI, 175 kg $ha^{-1}$ of K was detected, and in FRB, 120 kg $ha^{-1}$ of K was observed. FRR accumulated 200, 33, 95, 100, 30 and 30 kg $ha^{-1}$ of N, P, K, Ca, Mg and S, respectively.

## 4. Discussion

### 4.1. Soil fertility

Forest residue removal (FRR treatment) resulted in a reduction of SOC from 2 months to 11 years after treatment application. FRB resulted in a reduction of soil N from 2 months to 6 years, and FRR resulted in a reduction of soil N from 2 months to 13 years after treatment application (Fig. 1). At this site, Gonçalves et al. (2007) observed that FRB markedly decreased N mineralization in the 0–20 cm soil layer, reflecting the effect of high temperature on soil microorganisms. FRR also reduced N mineralization, reflecting a reduction of the substrate to microbiological activity. FRI markedly increased the initial mineralization; however, at 6 months after treatment application, FRM treatment showed the same amount. The burning of forest residues on soil in the FRB treatment markedly increased exchangeable bases and P availability, reflecting the mineralization promoted by burn. This finding stimulates rapid initial growth and high nutrient uptake (Figs. 3 and 4). After six months of burning, the availability of these nutrients returned to the initial status, and there was no difference among FRB, FRM and FRI treatments (Fig. 2 and Table 2). A larger difference in the availability of nutrients among the FRM and FRR treatments was not observed, likely reflecting low soil fertility, and after nutrient release from forest residue decomposition, a rapid uptake by trees was observed, inhibiting changes in soil fertility. A reduction in soil nutrient availability at R2 in FRR was observed, reflecting large nutrient outputs through harvesting.

The effects of site management on the soil properties, in general, were small and inconsistent across several sites (Nambiar and Harwood, 2014). Forest residue removal reduced the SOC and soil nutrient availability, consistent with the findings of Achat et al. (2015); however, this result was not observed at many sites (Laclau et al., 2010a; Mendham et al., 2003; Kumaraswamy et al., 2014; Nambiar and Harwood, 2014), likely reflecting soil buffer capacity, which would require more than one rotation with repeated forest residue removal affect soil nutrients (Mendham et al., 2014).

At 2 and 11 years after treatment application (24 months after plantation of R1 and R2, respectively), a small increase in available soil nutrients was observed. This increase likely reflects an increase in nutrient cycling through litter fall after canopy closure, which occurs approximately after two years in eucalypt plantations under these conditions (Laclau et al., 2010b).

### 4.2. Impact of site management on stand productivity (R1)

In R1, rapid nutrient mineralization through burning (Gonçalves et al., 2007) resulted in the highest wood volumes until the fourth year. FRI and FRM reached FRB in the third and fourth year, respectively (Table 2 and Fig. 3). No differences were observed between the FRM, FRI and FRB treatments at the end of R1 (eight years). The increased nutrient availability after the first two years (FRB) accelerated the growth rate; however, after canopy closure, the growth rate was reduced and stabilized, reflecting other limiting

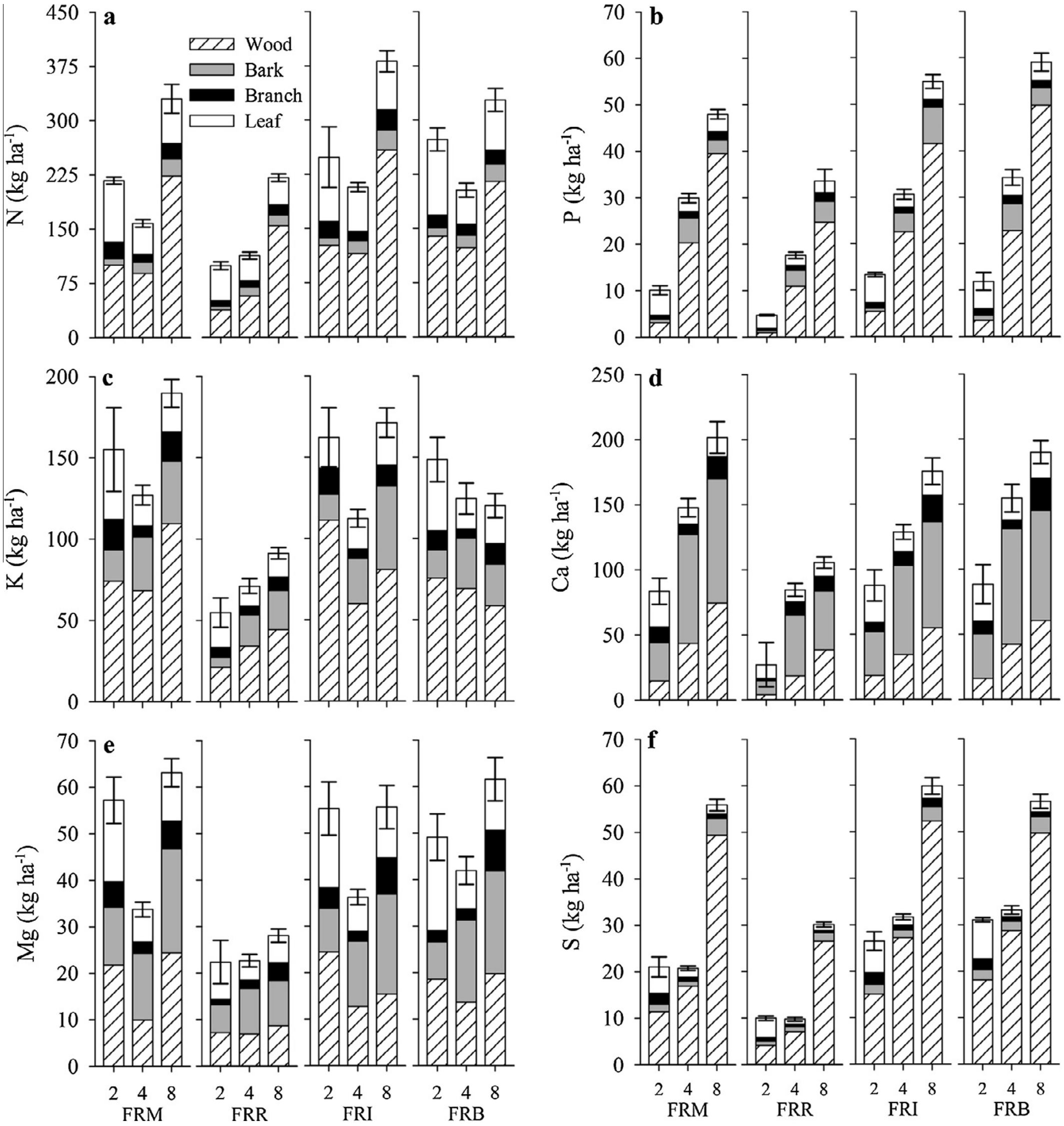

**Fig. 4.** N (a), P (b), K (c), Ca (d), Mg (e) and S (f) accumulated in aboveground components in the first study rotation of *Eucalyptus grandis* with different forest residue management at 2, 4 and 8 years old. Treatments: FRM - All forest residues were maintained on the soil, only stem wood harvest, FRR - All forest residues removal, FRI - All forest residues were incorporated in the soil at 0.2 m deep with heavy harrow and FRB – All forest residues on the soil were burned. The bars indicate of mean standard error of total accumulated.

factors (primarily water deficit; Stape et al., 2010). The initial growth in FRM and FRI was lower than that in FRB, as the microbial mineralization of nutrients is slower than the mineralization caused by burning (Jones et al., 1999; Gonçalves et al., 2007).

The incorporation of forest residues into soil increases the decomposition rate (Jones et al., 1999) and consequently increases nutrient mineralization (Gonçalves et al., 2007). Initially, the wood volume in FRI was higher than that in FRM. Forest residue removal (FRR) decreased wood productivity until the end of R1 (Fig. 3). The FRI had a higher wood volume; however, it did not differ from the FRM at the end of the rotations. Forest residue incorporation is not recommended, as this increases soil susceptibility to the erosion and degradation of its physical and biological properties, thereby increasing production costs (Gonçalves et al., 2002; Bertoni and Lombardi Neto, 2008).

The maintenance of forest residues in soil results in many benefits: (i) reduction of soil surface extreme temperatures (Gonçalves et al., 2000); (ii) soil protection against erosion (Gonçalves et al., 2002; Bertoni and Lombardi Neto, 2008); (iii) increased soil microbial activity (Mendham et al., 2002; Wu et al., 2011); (iv) increased nutrient mineralization (Nzila et al., 2002; O'Connell et al., 2004; Sankaran et al. 2008; Fernandez et al., 2009); and (v) reduced water lost through evaporation (Gonçalves et al., 2000; Matthews, 2005). Each of these benefits may have contributed to the higher productivity observed in FRM and FRI. However, the main benefit is the reduction of nutrient output (Du Toit et al., 2008; Deleporte et al., 2008; Laclau et al., 2010a; Achat et al., 2015). A larger amount of forest residue was maintained in soil, thereby increasing wood productivity (Fig. 5 and Laclau et al., 2010a), and was associated with nutrients outputs, primarily reflecting low soil fertility (Table 1) and low fertilizer application. A higher amount of fertilizer should be applied with the increased removal of forest residues. The maintenance of forest residues in soil can increase the cost of mechanized operations, demanding in many cases higher investments in technology to ensure silviculture quality.

Ca and P were the most limiting nutrients when forest residues were removed (LiM and FRR). This finding was verified through

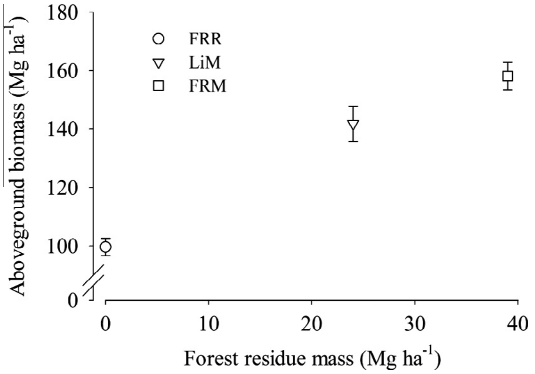

**Fig. 5.** Relationship between forest residue mass retained in the soil and aboveground biomass production at 8 years age in R1. Treatments: FRM - All forest residues were maintained on the soil, only stem wood harvest, LiM - only litter was maintained in the soil, FRR - All forest residues removed. The bars indicate of mean standard error.

foliar diagnosis. In FRM, FRI and FRB, after one year, the leaf concentration contained approximately 8.8 g kg$^{-1}$ of Ca and 1.7 g kg$^{-1}$ of P, and in FRR, the leaf concentration contained approximately 5.6 g kg$^{-1}$ of Ca and 1.4 g kg$^{-1}$ of P. The soil had a low availability of these nutrients (Table 1), and low amounts of P were applied in fertilizer and no Ca was applied. Approximately 13 kg ha$^{-1}$ of P was applied, although 30 kg ha$^{-1}$ should have been applied (according to Gonçalves, 2011). The K availability in the soil was also low, but an adequate rate of fertilizer was applied (140 kg ha$^{-1}$ of K). No difference between FRR and FRM concerning the leaf N, K, Mg and S concentrations was observed (data not shown).

The response to forest residue management in wood productivity in the present study was higher than the responses reported in 14 similar studies of eucalypt forests (Miranda et al., 1998; Jones et al., 1999; Nzila et al., 2002; Mendham et al., 2003; O'Connell et al., 2004; Du Toit and Dovey, 2005; Sankaran et al., 2008; Du Toit et al., 2008; Xu et al., 2008; Laclau et al., 2010a), even when compared with coniferous trees (Achat et al., 2015). Thus, under tropical wet conditions and low fertility soils, the maintenance of forest residues had a greater influence on the site productivity than temperate conditions.

### 4.3. Dynamics of biomass and nutrient accumulation

The treatments influenced the nutrient concentration in the aboveground compartments until the second year in R1. Larger nutrient concentrations were observed in FRB, and lower nutrient concentrations were observed in FRR (data not shown). Higher differences were observed with increasing age.

Leaf N concentration increased from the second to the fourth year of planting, stabilizing thereafter. In the branches, the N concentration had the highest values in the second year, gradually decreasing until 8 years. In bark, a higher N concentration was observed in the second year, followed by a reduction thereafter. This reduction in the N concentration in the trunk (bark and wood) with aging was consistent with the findings of Grove and Malajczuk (1985) and Laclau et al. (2000). The increase in the leaf N concentration with increasing age was consistent with the findings of Laclau et al. (2000). The trunk high N concentration and high biomass of the leaves and branches (compartments rich in N) increased N accumulation after two years, accounting for 70% of the total stock by the end of R1 for FRM, FRI and FRB. In FRR, reflecting low nutrient availability, N accumulation after two years represented 50% of the total stock by the end of the rotation. At that age, approximately 60% of the N accumulated in the aboveground parts was observed in the canopy; after four years, 40% was observed in the canopy; and after eight years, 30% was observed in the canopy. The reduced trunk N concentration and leaf biomass decreased the N accumulated in aboveground parts, from the second to the fourth year of R1, in FRM, FRI and FRB (Fig. 4). This effect was not observed in FRR, reflecting the low initial N accumulation. The lower N concentration in the trunk reflected N retranslocation to other compartments based on an increase in the heartwood proportion with aging (Sette et al., 2013).

From the second to fourth year, a moderate increase of the P concentration in the leaves, branches and bark was observed, decreasing thereafter. Wood P concentration was lowest in the first two years after planting, increasing in the following years. The P accumulation was proportional to the biomass accumulation, reflecting a low variation in the P concentration with increasing age (Fig. 4), consistent with Laclau et al. (2000). In the initial stage of forest development (two years), the highest nutrient amount was observed in the canopy (leaves and branches). From the fourth year to the end of the rotation (eighth year), more than 70% P was accumulated in the wood, and less than 10% P was accumulated in the canopy by the eighth year. Most of the P accumulated in aboveground components is exported through harvest; thus, the application of a P fertilizer is necessary to avoid a decrease in wood production.

The K content in the leaves, branches, bark and wood decreased with increasing age. In the wood, the K concentration was reduced by approximately 75% from the second to the fourth year, consistent with Laclau et al. (2000), but with lower K concentrations. More than 70% of the K content in the aboveground components at the end of the rotation was accumulated until the second year (Fig. 4). In R1, the amount of K accumulated after two years was higher than the amount accumulated after eight years in the FRB treatment. This reduction of accumulated K reflects a pronounced reduction of the wood K concentration and leaf biomass (compartment rich in K), suggesting that K fertilizer should be applied in the early stages. At the end of the rotation, less than 50% K accumulated in aboveground parts was contained in the wood. A larger amount of K was detected in the leaves and bark; thus, when these components are removed through harvest, elevate levels of K fertilizer application may be necessary.

Leaf and branch Ca concentration showed a mild reduction with stand age primarily between two and four years after planting. A low Ca content was observed two years after planting (30% of amount accumulated until eight year) compared with other nutrients (Fig. 4). Considering only wood, at two years, only 10% of the total Ca was accumulated. From the second to the fourth year, an increase in the Ca accumulated in the aboveground components was detected. At the end of the rotation, 50% Ca accumulated in the aboveground compartments was detected in the bark, and only 30% Ca was accumulated in the wood. When the bark is removed through harvest, additional Ca fertilizer application may be necessary.

Except in the branches, the Mg concentration reduced with stand age. In the wood, this reduction was higher from the second to the fourth year and remained constant from the fourth to the eighth year. Higher Mg accumulation was observed in the second year, representing more than 60% of the total Mg accumulated in the eighth year (Fig. 4). Approximately 40% of the Mg accumulated in aboveground compartments after eight years was observed in the bark, while 40% Mg was observed in the wood and 20% Mg was observed in the canopy.

The S concentration in the aboveground compartments showed a slight reduction from the second to the fourth year, remaining constant thereafter. A similar S concentration was observed in all aboveground compartments. The S accumulation exhibited the same behaviour as the biomass (Fig. 4). More than 80% of S accumulated in the aboveground compartments was observed in the wood.

Except for P and Ca, the treatments in R1 increased nutrient availability (FRM, FRI and FRB) and increased the accumulation of nutrients until the second year, which were, in some cases, higher than that observed after four and eight years. In FRR, reflecting low nutrient availability, the nutrient accumulation was almost proportional to the biomass. When higher available nutrients were observed, the stand nutrient uptake increased in the initial growth stage, increasing the concentration in the tissues and increasing biomass accumulation, particularly in the leaves. After the early growth phase, a portion of these nutrients was deposited onto the soil or was retranslocated, promoting nutrient cycling and increasing the soil nutrient availability from two years onward (Fig. 2). This finding might represent a strategic behaviour of eucalypt plantations to provide higher competitive ability.

### *4.4. Nutrient balance*

Other compartments beyond the stem wood can be harvested, depending on the harvest system and purpose of the forest plantation. When the purpose is biomass production, in addition to stem wood, bark, branches, leaves and even the litter layer could be harvested. Considering nutritional and soil conservation aspects, a suitable harvest system in wet tropical conditions is one that harvests only the stem wood and maintains the other compartments (leaves, bark, branches, litter layer and roots) on the soil (Gonçalves et al., 2013; Nambiar and Harwood, 2014; Achat et al., 2015), reflecting the importance of forest residue on soil conservation, as wood is the compartment with the lowest nutrient concentrations (Laclau et al., 2000). We observed that one ton of stem wood comprises only 4 kg of macronutrients (N, P, K, Ca, Mg and S). The leaves, branches, bark and litter layer have 37, 16, 23 and 20 kg Mg$^{-1}$ of macronutrients, respectively.

Less than 40% of the macronutrients accumulated in aboveground components were detected in the stem wood, except for S, which showed 80% accumulation in stem wood. Approximately 30% of macronutrients were accumulated in the litter layer. The maintenance of forest residues on the soil significantly contributes to the release of N, Ca, Mg and S. Bark contains a large amount of Ca, Mg and P; thus, when this material is harvested, special attention to fertilizers containing these nutrients should be given.

In FRM, 125 Mg ha$^{-1}$ of biomass and 502 kg ha$^{-1}$ of macronutrients were harvested, while in FRR, 164 Mg ha$^{-1}$ of biomass and 1342 kg ha$^{-1}$ of macronutrients was harvested (Table 3). In terms of nutrient balance, these nutrients are not sustainable. Wood production in the long term is highly dependent on forest residue management. The unsustainability of treatments with nutritional constraint reflect three major factors: (i) low fertilizer application; (ii) high nutrient output, reflecting high wood productivity; and (iii) low soil fertility. Only the K in the FRM treatment showed a positive nutrient balance, reflecting fertilizer application. All other macronutrients had a negative nutrient balance, thereby limiting the wood productivity in future rotations.

### *4.5. Site recovery potential*

In the present study, a long-term effect of forest residue removal on tree growth, SOC and total N of soil and a short-term effect on the soil nutrient availability were observed. Residue removal decreased the wood productivity by approximately 40% in R1. In R2, even when maintaining all forest residues on the soil, after R1 harvesting, there was a significant decrease in wood production (6%). Forest residue removal increases nutrient removal

**Table 3**

Nutrient stocked in the soil and forest biomass, inputs and outputs of nutrients in two crop rotations.

| Component | Biomass (t ha$^{-1}$) | N (kg ha$^{-1}$) | P (kg ha$^{-1}$) | K (kg ha$^{-1}$) | Ca (kg ha$^{-1}$) | Mg (kg ha$^{-1}$) |
|---|---|---|---|---|---|---|
| *Nutrients stocks* | | | | | | |
| Stock in the soil (0–100 cm)[a] | | 728 | 38 | 121 | 193 | 84 |
| *Stock in the forest biomass* | | | | | | |
| Litter layer | 24 | 187 | 10 | 36 | 209 | 24 |
| Stem wood | 125 | 224 | 19 | 106 | 110 | 16 |
| Stem bark | 9 | 36 | 12 | 47 | 95 | 15 |
| Canopy | 6 | 73 | 8 | 29 | 43 | 12 |
| Root | 24 | 98 | 4 | 29 | 33 | 10 |
| Total | 188 | 617 | 52 | 247 | 489 | 76 |
| Total | | 1345 | 90 | 368 | 682 | 160 |
| *Harvest outputs* | | | | | | |
| Treatment FRM | 125 | 224 | 19 | 106 | 110 | 16 |
| Treatment LiM | 140 | 332 | 38 | 183 | 248 | 43 |
| Treatment FRR | 164 | 520 | 48 | 218 | 456 | 67 |
| *Inputs* | | | | | | |
| Fertilizer application[b] | | 15 | 13 | 137 | | |
| Atmospheric deposition[c] | | 32 | – | 32 | 51 | 13 |
| *Nutrient balance*[d] | | | | | | |
| Treatment FRM | | −177 | −6 | 62 | −59 | −4 |
| Treatment LiM | | −286 | −25 | −14 | −197 | −30 |
| Treatment FRR | | −473 | −35 | −50 | −405 | −54 |
| *Nutrients stored*[e] | | | | | | |
| Treatment FRM | | 1168 | 84 | 431 | 623 | 156 |
| Treatment LiM | | 1059 | 64 | 354 | 485 | 130 |
| Treatment FRR | | 872 | 55 | 319 | 277 | 106 |

[a] The soil contributions was determined by analysis of P, K, Ca e Mg by resin extraction method (Table 1) and to N was considered that 10% of total N is mineralizable (Pulito et al., 2015).

[b] It was considered that 100% of fertilizer application was available.

[c] Laclau et al. (2010b).

[d] Inputs less outputs.

[e] Initial stock plus nutrient balance.

and consequently decreases the nutrients available for trees, affecting growth. The nutrient stocks in the soil are also reduced (Table 3), affecting growth in the following rotation. This finding was in contrast to that of Achat et al. (2015) in a meta-analysis concerning forest residue management worldwide. A majority of the trials utilized in this analysis were conducted under temperate climates with low weathered soil, that is, higher nutrient stocks. In tropical climates with highly weathered soils, forest residue removal significantly impacts wood productivity compared with temperate climate. Thus, the sites under tropical conditions are more dependent on organic residues to provide nutrients and reduce surface evaporation (Tiessen et al., 1994; Matthews, 2005).

The FRB treatment showed high wood productivity in R1, reflecting rapid mineralization promoted by fire. However, in this site, Gonçalves et al. (2007) observed losses of 86% of N, 60% of P, 49% of K, 11% of Ca, 29% of Mg and 84% of S accumulated on forest residues by burn. These losses amounted to around 254, 17, 55, 38, 15 and 33 kg ha$^{-1}$ of N, P, Ca, Mg and S. Although rapid nutrient mineralization the forest residue burn resulted in substantial nutrients losses, it resulted in losses of wood productivity in R2 (Fig. 3).

The difference between the FRM and FRR treatments was reduced by 40% in R1 to 6% in R2, reflecting two main factors: (i) maintenance of all forest residues on the soil after the harvest of R1; (ii) lower nutrient outputs with R1 harvesting in the FRR compared with FRM treatment, reflecting low growth and consequently low nutrient accumulation in R1. These results indicate that potentially more than 16 years are required for the total recovery of the site yield after inadequate site management. Indeed, 11 and 13 years were needed to completely recover the soil C and N concentrations, respectively (Fig. 1).

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